PROCEEDINGS OF SCIENCE

Spin physics

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The spin structure of the nucleon is still not very well understood but great progress has been made to understand how much the quark and gluon helicities contribute to the proton spin. In particular recent results from RHIC clearly show a substantial nonzero gluon spin contribution in the accessed x range and the remaining goal is to extend the range down as much as possible - initially with several remaining RHIC measurements and eventually at an EIC. Updated polarized DIS results improved the precision on the quark helicities while single longitudinal spin asymmetries in the W production of proton-proton collisions indicate an asymmetric, polarized light sea. The transverse spin stucture and exclusive processes opened the way to study the QCD dynamics inside the proton and the hard process, culminating in the prediction of the sign change of the Sivers function when extracted in semi-inclusive DIS and the Drell-Yan(DY) process. While the COMPASS experiment DY measuerments using a pion beam are still being analyzed, first results from the STAR experiment using fully reconstructed W transverse single spin asymmetries indicate a preference for a sign-change scenario. Closely related to these DY-type measurements and other transvserse spin measurements is the theoretical progress and need for experimental input in order to quantitatively describe the evolution of objects explicitly depending on instrinsic transverse momentum. In addition several new deeply virtual compton scattering and hard exlusive meson production measurements increase the amount of information on generalized parton distribution functions and first, more global, DVCS fits become available.

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1. Introduction

The spin structure of the nucleon allows us to study aspects of QCD which are often not directly accessible otherwise. In particular, many transverse spin as well as exclusive processes allow to probe the QCD dynamics. In addition, there have been plenty of surprises related to single or double spin asymmetry measurements which helped us revisit our understandign of QCD and improve it.

2. Longitudinal spin structure

The longitudinal spin structure has traditionally been the main interest in QCD spin physics after the discovery that the contribution of quark spins in the x range then measured was substantially smaller than what the relativistic quark model predicted [1]. This is generally known as the *spin-crisis* and many experiments since the EMC experiment have contributed to understand the quark and gluon spin contributions better since. At present the covered x range is still limited predominantly to regions $x > 5 \times 10^{-3}$ for most polarized inclusive and semi-inclusive DIS measurements as well as proton-proton collisions. The most recent results include the final inclusive g_1 measurements from COMPASS [2]. The existing JLAB data and its future 11 GeV extension will cover the highest x which are not too well constrained either but with rather limited impact on the total quark spin contributions due to the smallness of the unpolarized distribution functions there. It will nevertheless be of interest in distinguishing various theory predictions about the $x \to 1$ behavior. In order to include these relatively low scale measurements, several theory groups have started to include higher twist and target mass effects in their fits. First results of the JAM collaboration [3] for only inclusive measurements so far do now exist and they are preparing for more global fits including SIDIS and pp measurements to get sensitivity to individual quark flavors without relying entirely on axial and hyperon decay constants. All DIS and SIDIS related measurements so far do not provide enough lever arm in Q^2 to extract the gluon spin contribution from DGLAP evolution since only fixed target data exists. The recent measurements at the polarized proton-proton collider RHIC at a center-of-mass energy of 200 GeV provided the first evidence of a nonzero gluon spin contribution via the main channels of single jet [4] and pion [5] double spin asymmetries A_{LL} at mid-rapidity. Global fits including this data did indeed find substantial gluon spin contributions in the accessed x range $0.05 < x < 0.2$ [7, 8, 9]. Extrapolating these results to the whole x range the gluon spin contribution could be the dominant contribution in the spin sum-rule and even a scenario without any net orbital angular momentum contribution to the sum-rule is possible [10]. In the past few years RHIC has been running at a higher center-of-mass energy of 510 GeV. The first results from this energy are now available and clearly confirm the nonzero asymmetries and the resulting gluon spin contribution [11, 12]. The higher energy also allows to extend the covered x range down to 0.01 and the higher accumulated luminosity allows to access di-jet asymmetries where the x of the two participating partons can be better localized [13]. See Fig. 1 for the relevant pion and di-jet asymmetries at 510 GeV compared to various parameterizations.

In order to increase the x coverage with the existing range of available experiments and energies, asymmetries at more forward regions in proton-proton collisions can be extracted. Due to the rapidly rising unpolarized PDFs the expected asymmetries generally become much smaller and a

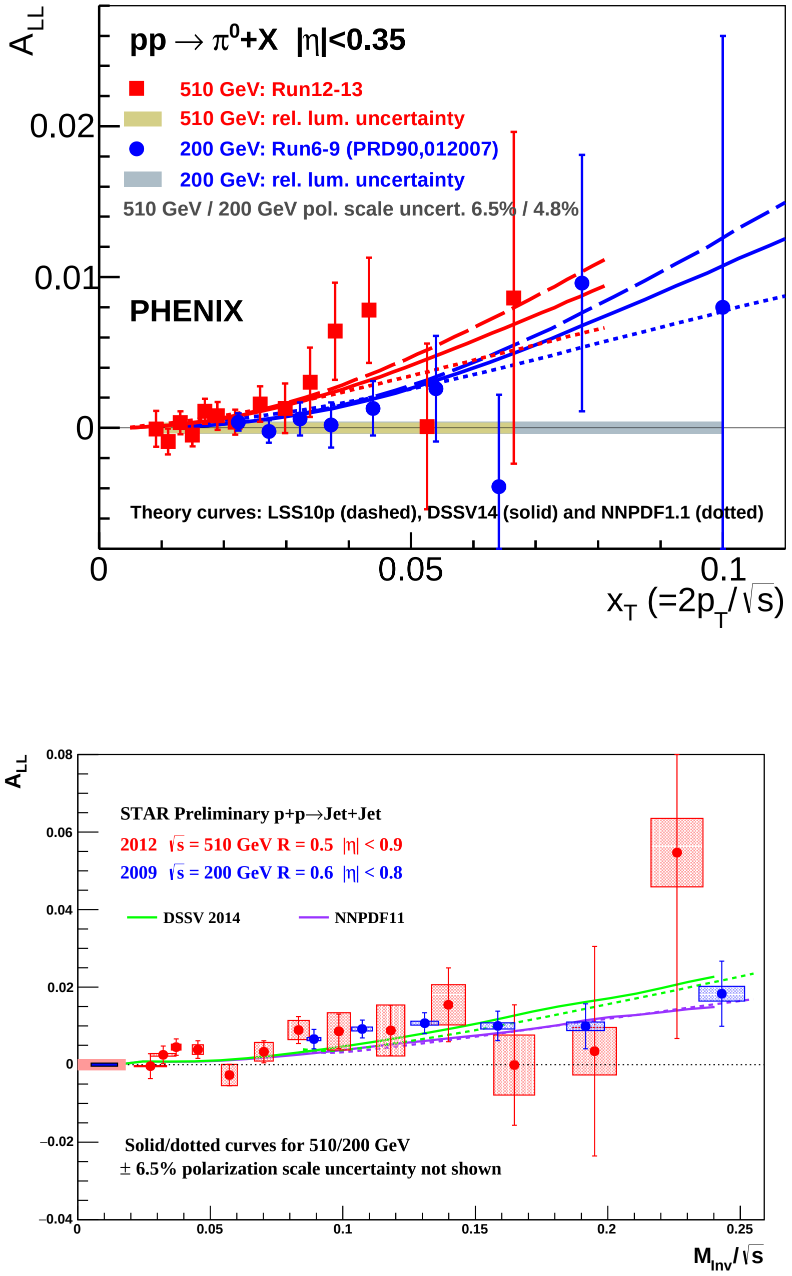

Figure 1: Top: PHENIX neutral pion double spin asymmetries at collision energies of 200 GeV (blue) and 510 GeV (red) as a function of $x_T = 2P_T/\sqrt{s}$. The corresponding parameterizations using the DSSV14, NNPDFpol1.1 and LSS10 global fits are also shown (red and blue lines, respectively). Bottom: Preliminary STAR di-jet double spin asymmetries at collision energies of 200 GeV (blue) and 510 GeV (red) as a function of $M_{inv}/\sqrt{s}$ as well as DSSV14 (green lines) and NNPDFpol1.1(purple lines) curves.

very high precisions in the measurements needs to be achieved. Pion measurements in rapidities of up to 3.9 are currently ongoing which can reach x of around 0.001. Additionally, the relatively clean J/ψ asymmetries in rapidities between 1.2 and 2.2 have been extracted [14]. At RHIC energies J/ψ are almost entirely produced from gluon-gluon scattering and at forward rapidities the x of the participating partons also extends down to $2 \times 10^{-}3$ for the backward going proton while the forward going parton is in the range where the polarized PDFs are now already reasonably well known. While all measurement points, shown in Fig. 2, are consistent with zero an overall tendency toward positive asymmetries is visible. Assuming that the partonic analyzing power is $+1$ as in some NRQCD J/ψ production mechanism models one can reweight the NNPDFpol1.1 replicas. The resulting gluon helicities are indeed shifted toward positive values while the uncertainties do not change substantially due to the limited precision of the data.

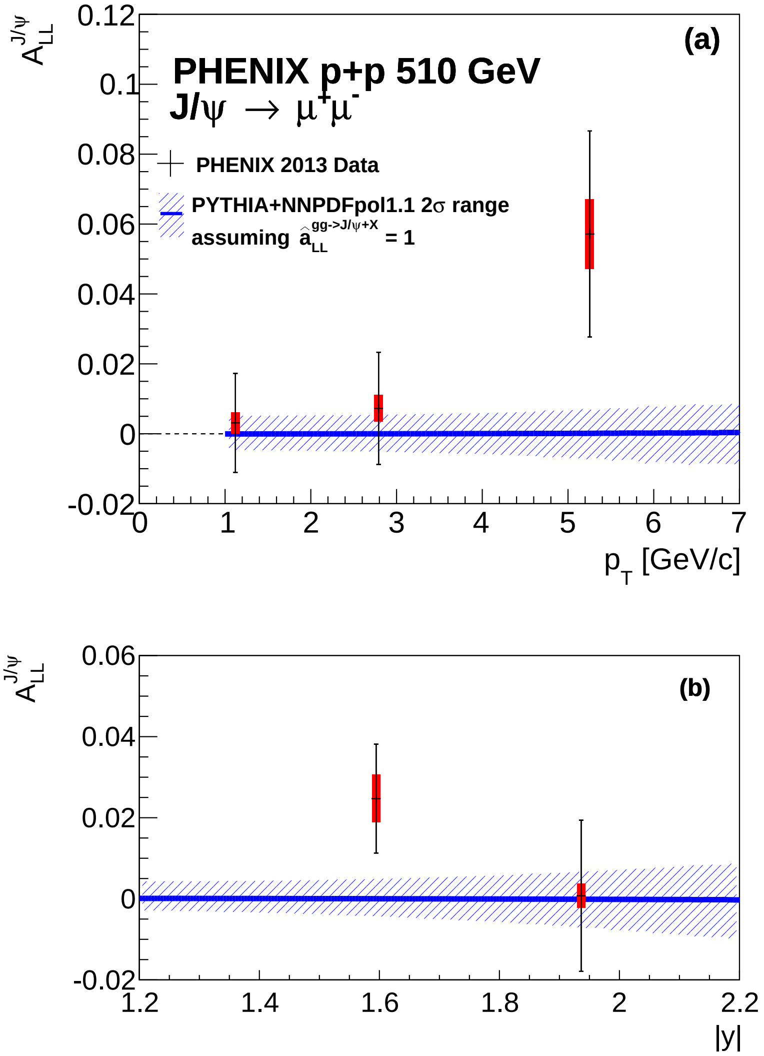

Figure 2: J/ψ double spin asymmetries as a function of P_T and y. The corresponding parameterizations using the NNPDFpol1.1 global fits and assuming a partonic analyzing power of $+1$ are also shown (blue lines and band).

The sensitivity to sea quarks from SIDIS measurements is at present also limited due to the *u* quark dominance as well as the knowledge of fragmentation functions. In contrast, real W production in longitudinally polarized proton collisions can access sea quark helicities rather well at a very high scale and without the need of fragmentation functions. In addition, the charge of the W singles out predominantly one quark and one anti-quark flavor each with the quark helicities already reasonably well known. The recent measurements of single spin asymmetries from RHIC indicate a asymmetric light sea which disfavors several pion cloud based models of the nucleon while being consistent with other models. [15, 16]

3. Transverse spin structure

The transverse spin structure studies only gained renewed interest in the last decade. Two mechanisms, initially proposed to explain large transverse spin asymmetries in fixed target hadron-hadron scattering were explicitly measured to be nonzero in semi-inclusive DIS [17]. Both mechanisms, the Sivers function [18] and the Collins fragmentation function [19] depend on explicit transverse momentum dependence (TMD) in the nucleon or the fragmentation and create left-right asymmetries. Initially the Sivers function was thought to be zero due to naive time-reversal invariance [19], but later it was realized that the gauge links in the bi-local operator definition cannot be ignored when intrinsic transverse momentum is involved [20, 21]. As a consequence Collins predicted that the universality of the Sivers function needs to be modified as the sign between that extracted in SIDIS and in the Drell-Yan (DY) process to be opposite [22]. The Sivers function in SIDIS has been by now well measurements to be nonzero by the HERMES [17, 23] and COMPASS [24, 25] experiments. However, until very recently no polarized Drell-Yan measurements were available. The COMPASS experiment has been running in recent years a dedicated Drell-Yan campaign including a π^- beam of 160 GeV on a transversely polarized target and several modifications to handle hadronic beams, most notably a large, hadronic absorber downstream of the target including some additional vertexing capability. The COMPASS Drell-Yan data is currently being analyzed and the expected precision should be sufficient to clearly confirm or reject the sign-change of the Sivers function. Meanwhile, the STAR experiment published results from a test-run on fully reconstructed W transverse single spin asymmetries [26]. By reconstructing as much of the recoiling fragments in addition to the W decay electron and W identification via missing away-side activity the actual W transverse momentum can be extracted and these asymmetries be calculated. The limited statistics do clearly favor a sign-change scenario over no sign-change when assuming no additional TMD evolution effects as can be seen in Fig. 3 using the DY predictions of [27]. A dedicated run in 2017 is planned to substantially reduce the uncertainties on the W measurements as well as add Z and Drell-Yan measurements as well.

However, while the first indication of the expected Sivers function sign-change is very promising, the theoretical uncertainties due to the size of TMD evolution effects are still huge. While several groups of theorists mostly use the same CSS [28] formalism, unlike its application for Higgs production or similarly heavy particles, the bulk of the existing TMD SIDIS data exists at transverse final state momenta which are too small to be treated perturbatively. As such, again non-perturbative terms play an important role and need to be determined from experimental data as well and often even the functional dependence of these terms is not well known. As a consequence the size of various asymmetry predictions to the DY measurements including TMD evolution based on

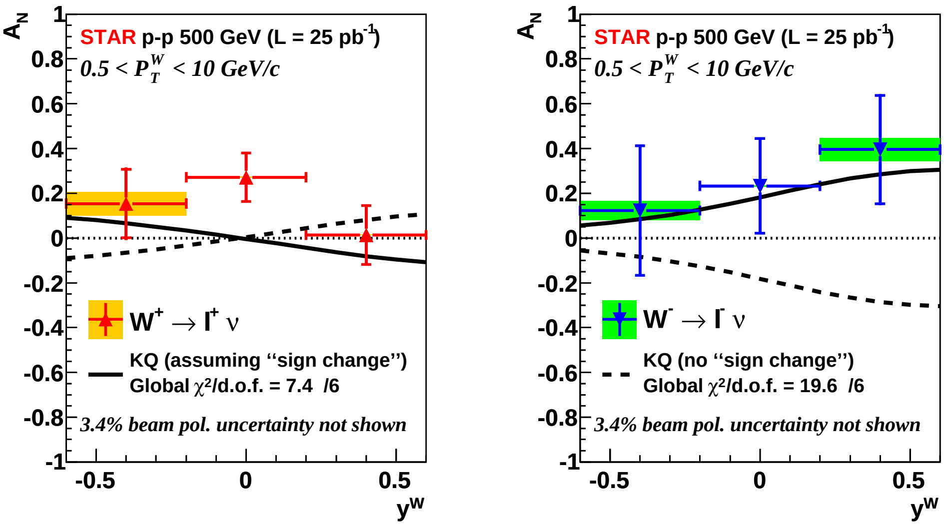

Figure 3: W single spin asymmetries from the STAR experiment .

the SIDIS measurements are varying substantially and only more DY(and heavy boson) data will really tell. Apart from the two already mentioned DY-type measurements also a third polarized DY measurement is being planned. Using the 120 GeV unpolarized proton beam from Fermilab's main injector on a polarized hydrogen target should give additional access to predominantly the anti-u quark Sivers function which so far is hardly constrained by the SIDIS measurements.

The other very prominent function is the Collins fragmentation function which relates the transverse spin of an outgoing parton with the azimuthal distribution of final state hadrons. Being chiral-odd, it can be used to access the quark transversity distribution in the nucleon which relates to the last leading twist structure function related to the tensor charge of the nucleon. Several SIDIS measurement of Collins-type asymmetries exist [17, 25, 30] from which the quark transversity distributions can be extracted after including the Collins fragmentation function measurements from electron-positron annihilation measurements [29, 31, 32]. In recent years more results on the Collins FF have become available, Babar has measured both the explicit transverse momentum dependence of Collins FF related asymmetries but also extracted kaon related asymmetries [33] which will be important to get a handle on the strange quark transversity. Not only from the B-factory experiments but also at lower center-of-mass energies [34] results become available. While these latest results are not yet included in all global fits of the SIDIS and e^+e^- data, several parameterizations are available now including the kaon results [35] or explicitly transverse momentum dependence and evolution [36]. Similarly, several results directly related to transversity have been obtained from RHIC in both the interference fragmentation channel [37] as well as preliminary results on Collins-type asymmetries for hadron modulations relative to the jet axis [38] both at center-of-mass energies of 200 and 510 GeV. Neither of these two results have yet been included in global fits, but the Collins results at the two different energies suggest only small TMD evolution effects.

3.1 Polarized p-A collisions

In the last year, RHIC has been operated with a polarized proton beam colliding with Au and Al beams. While the origin on the large forward transverse single spin asymmetries in p-p collisions is still not well understood, several models studied the nuclear dependence under the assumption of only initial or final state processes causing these asymmetries in proton-proton collisions [39, 40]. At forward rapidities of 3-4 where the initial asymmetries were found, the x of the participating parton from the nuclear beam is small and potentially nonlinear effects might be visible and result in decreasing asymmetries on nuclear beams. A preliminary result by the STAR experiment [41] comparing the proton-proton and proton-Au data sees no significant change in the size of the asymmetries within the uncertainties as shown in Fig. 4.

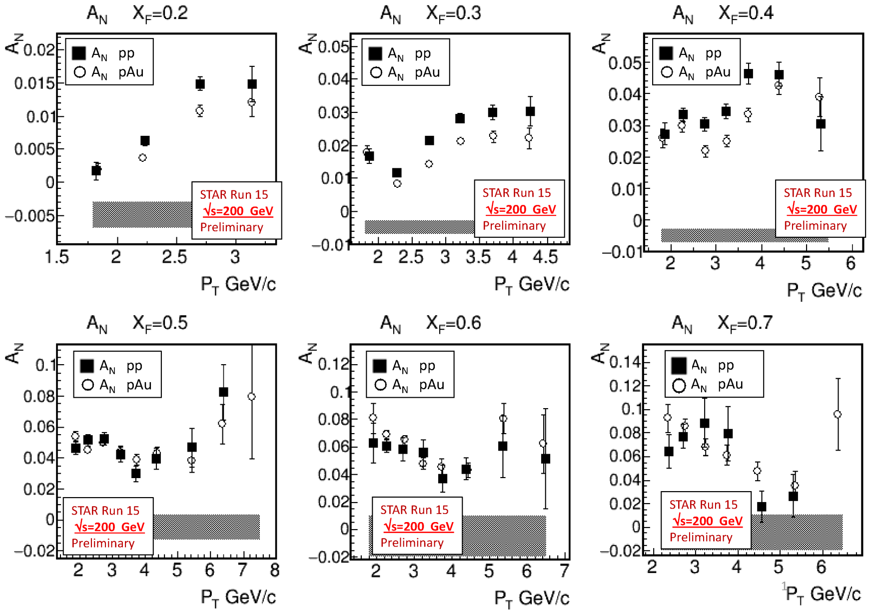

Figure 4: Neutral pion transverse single spin asymmetries at collision energies of 200 GeV in proton-proton (blue) and proton-gold (red) collisions.

At very forward rapidities ($\eta > 6$), neutron single transverse spin asymmetries in proton-proton collisions have been measured at various energies and were used as diagnostic tools at RHIC. These asymmetries are generally described by Regge behavior [43]. However, in polarized proton-nucleus collisions, the asymmetries turned out to be changing sign and be substantially larger in magnitude on Au beams as seen by the PHENIX experiment [42], see Fig. 5. This would indicate other contributions playing a role as well. A trigger vetoing activity in the beam-beam collision counters (BBCs, which are most sensitive for hard processes as well as diffractive processes with at least one beam remnant breaking up) indeed finds even larger and positive asymmetries on Al and Au beams while coincidence with the BBCs results in asymmetries of the same sign as in proton collisions.

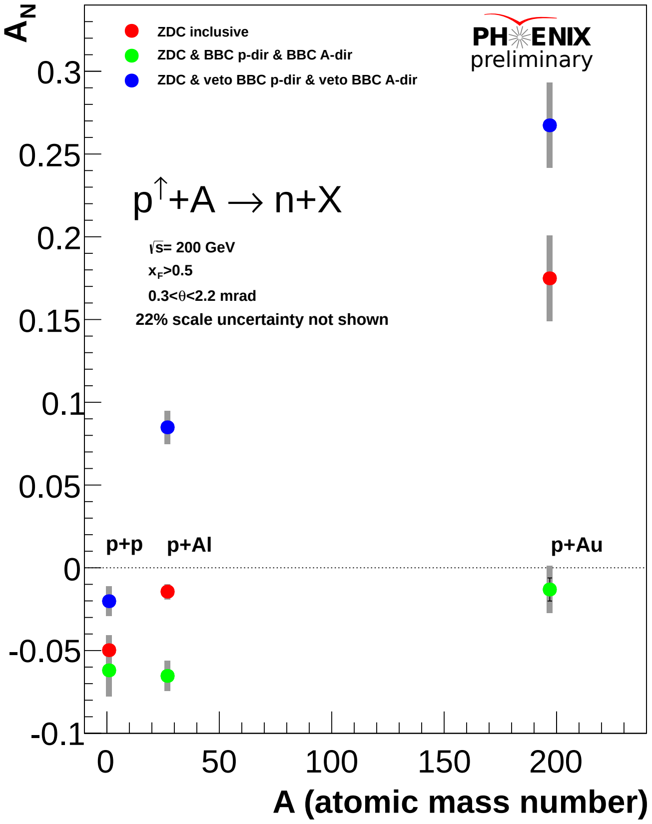

Figure 5: Preliminary forward neutron single spin asymmetries in proton-proton, proton-Al and proton-Au collisions as obtained in the PHENIX experiment. The data using the Zero Degree Calorimeter (red) only, coincidence with (green) as well as veto against (blue) the beam-beam counters are shown.

4. Generalized parton distributions

Generalized parton distribution functions can be accessed in various exclusive reactions, most prominently in deeply virtual Compton scattering, DVCS. The main reason to study GPDs is their relation to the total angular momentum J of quarks [44]. In addition GPDs allow to study not only the longitudinal momentum distribution of quarks and gluons but also their (transverse) spatial structure. GPDs reduce to the regular PDFs as well as form factors under certain limitations and integrations. While unpolarized DVCS measurements were already performed by the HERA collider DIS experiments, polarized DVCS measurements so far are only available from fixed target DIS experiments where various combinations of beam-spin, target-spin and beam-charge asymmetries were extracted which single out different reduced Compton form factors and their related GPDs. With the increasing amount of data [45, 46], DVCS fits start becoming more global in trying to fit and describe various types of measurements and from various experiments. The boundaries of the comparatively well known PDFs and form factors are being fulfilled in more recent fits [47] while previous models failed to describe them correctly. In addition to DVCS also exclusive meson production provides important GPD information. In particular in transverse spin asymmetries the poorly known transverse GPDs $E_T, H_T, \tilde{E_T}, \tilde{H_T}$ can be accessed. Several exclusive pion, ρ and ω measurements became available in the past year[48].

5. Summary

In summary, recent results have been substantially improving the understanding of quark, sea-quark and in particular gluon spin contributions to the total spin of the nucleon. With moderate improvements predominantly at high x at JLAB, the remaining low-x contributions will be accessed eventually at an electron-ion collider. The corresponding quark orbital angular momentum will also be accessed there in polarized DVCS at collider energies. For the transverse spin structure we will either confirm or refute the predicted sign-change of the Sivers function from SIDIS to Drell-Yan. The general transverse spin related measurements will move from a discovery phase to a precision phase including better understanding of TMD evolution and, thanks to the TMD-higher-twist connection, a theoretical treatment beyond leading order. As a consequence, more channels will enter into the global parameterizations of the various transverse spin effects, in particular proton-proton collision results. More exclusive processes will be studied both in DIS at JLAB and EIC but also in polarized proton-proton and proton-nucleus collisions. As the past has shown, there are likely more surprises in the understanding of QCD to be had by performing spin related measurements.

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